arXiv:astro-ph/0611773 v1 24 Nov 2006

# Neutrino astronomy with IceCube and AMANDA

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**Abstract.** Since the early 1990s, the South Pole has been the site of the construction of the world's first under-ice Cherenkov neutrino telescopes - AMANDA and IceCube. The AMANDA detector was completed in 2000, and its successor IceCube, a kilometre scale neutrino detector, began construction in 2005. Completion of IceCube is scheduled for 2011. This paper will give an overview of the history, construction, latest physics results and potential of these detectors.

## 1. The appeal of neutrino astronomy

The road to a kilometre scale neutrino detector, pioneered by the DUMAND collaboration, has seen the operation of the first generation experiments, AMANDA and Lake Baikal, as well as initial construction and planning for IceCube, ANTARES, NESTOR, NEMO and KM3NET. The discovery of neutrinos with these detectors will hopefully extend and complement the knowledge of the universe to date gained through cosmic ray and gamma ray observations. While the nature and location of the cosmic ray sources are unknown, there are many confirmed sources of TeV gamma-rays. If one of these turned out to also be a neutrino source, then a hadronic accelerator central engine might be driving cosmic ray, gamma and neutrino production [2].

A neutrino detector like IceCube or AMANDA uses an array of photomultipliers to record Cherenkov light from through-going muons, or from point-like shower ("cascade") events. Muons result from charged current interactions of neutrinos in the detector volume, or in the surrounding ice and rock. Cascade events result from charged and neutral current interactions of all neutrino flavours.

The backgrounds to a search for a flux of high-energy extra-terrestrial neutrinos at the earth are atmospheric muons and neutrinos from the interaction of cosmic rays in the earth's atmosphere. The atmospheric muons are eliminated by looking for events moving upward through the detector – only neutrinos can penetrate the earth. A small fraction of the large downgoing muon flux will be falsely reconstructed in the upward direction. These are removed by tight requirements on the fitted track. After atmospheric muons are eliminated, there is a flux of atmospheric neutrinos seen in a detector. This can be used as a calibration test beam to check the understanding of the detector, or be used to look for new neutrino physics. A search for point sources of neutrinos is made by looking for an excess of events from a direction in the sky. Electromagnetic observations by other detectors may provide information to reduce the time over which such a search is made - for instance in a search for neutrinos correlated with a gamma-ray burst. One can also look for a diffuse excess of neutrinos from the sum of all sources in the universe. Since the extra-terrestrial flux predictions tend to go as $dN/dE \sim E^{-2}$, one looks for higher energy events in the detector to separate them from the more steep atmospheric neutrino spectrum ($dN/dE \sim E^{-3.7}$).

## 2. Physics results from AMANDA

The first detection of muon Cherenkov radiation in polar ice was made in Greenland in 1990 [3], using three photomultipliers deployed to a depth of about 200 metres. Following this success, similar tests were made at the South Pole over the next years, with the AMANDA-A detector deployed in 1993-94 [4]. Construction of the presently operating AMANDA detector took place from 1995 to 2000, over which time 677 optical modules were deployed over 19 strings, to depths ranging from 1500 to 2000 metres. The properties of the polar ice, critical for understanding of the detector, have been measured using light sources in the array [5]. Although most of AMANDA used analogue signal technology, digital technology, eventually chosen for IceCube, was tested on one string [6].

### *2.1. Atmospheric neutrinos*

While three neutrino candidates were observed with the first four strings of AMANDA [7], the first compelling evidence of high-energy atmospheric neutrinos came from the 10 string 1997 data set, where 16 upgoing events were left after data reduction [8]. Dramatic improvements in the analysis techniques [9] increased this number to about 300 [10, 11]. Over the entire life of AMANDA-II, many thousands of atmospheric neutrinos have now been observed [12, 13]. These are the highest energy neutrinos ever observed. The observed rate is consistent with the uncertainties in theoretical predictions [14, 15]. A regularised unfolding technique has been used to make a best-fit to the originating energy spectrum; again consistency with expectation is seen [16]. The agreement of the atmospheric neutrino measurements with expectations shows that the detector is working as expected.

### *2.2. Point sources*

Several searches for northern hemisphere point sources of neutrinos have been conducted with the AMANDA detector, for the 1997 [17], 2000 [18] and 2000-02 [19] data sets. The most recent search used data from 2000-04, corresponding, after correction for down-time of the detector, to 1001 days of live time [12, 13]. The final event set consists of 4282 upward moving events, believed to be atmospheric neutrinos. Several search methods were used to look for point sources in the northern sky. For each, the expected background for any source is found from off-source data from the same declination band. The expected sensitivity is found from simulations of neutrino interactions, muon propagation, and the full detector response to the Cherenkov light emitted. Full-sky searches (looking for a hot spot anywhere in the sky), specific source searches, and stacking searches were conducted. The full-sky and specific source searches were optimised in an unbiased fashion to produce the best limit setting potential [20]. The 90% confidence level sensitivity of the full-sky search to an $E^{-2}$ flux (assumed to have a $\nu_\mu : \nu_\tau$ ratio of 1:1), relatively constant with declination, is about $\mathrm{E}_\nu^2 \times \mathrm{dN}_\nu/\mathrm{dE}_\nu < 10^{-10}$ TeV cm$^{-2}$ s$^{-1}$. The numbers of observed events across the sky were consistent with the background expectations, leading to the same result for the average all-sky experimental limit. The highest significance seen was $3.7\sigma$ and, via scrambled random sky maps, the probability of seeing something this significant or higher was found to be 69%. Searches for 32 specific candidate sources, and searches made where the events from objects belonging to common classes were summed, were made. Limits were placed on the neutrino fluxes from the objects [21, 13]. For a source above the horizon, SGR 1806-20, a search for muons from both neutrinos and gamma-rays was made. With no significant signal seen, limits were placed on the gamma and neutrino fluxes from the source [22]. While not truly a point source, the galactic plane was searched for an excess of neutrinos from cosmic ray interactions with the dust, using similar methods as employed in the point source searches. No excess of events was seen and limits on models were set [23].

*2.3. GRBs*

Gamma-ray bursts are some of the most energetic phenomena in the universe, with emission timescales as short as seconds. During the life of AMANDA, satellites such as the CGRO, with the BATSE detector, and the IPN satellites, including HETE and Swift, have recorded gamma emissions from many GRBs. Waxman and Bahcall theorised that GRBs may be the source of the highest energy cosmic rays [24]. In this "fireball" model, neutrinos would also be produced. The AMANDA data has been searched for neutrinos in spatial and temporal coincidence with about 400 GRBs [25]. The addition of a time cut on the search greatly reduces the expected background to of order one event over the sum of all GRBs searched. No event has been observed in coincidence with a GRB, consistent with this small total expected background. Limits on the fluxes from all bursts, classes of bursts, and individual bursts, have been placed. The limits from all bursts are within a factor 4 of the Waxman-Bahcall prediction. In another analysis, the observations from each individual burst are interpreted in light of all information known about that burst from other wavelengths, via an individually calculated neutrino flux. An analysis of this type has been performed for GRB030329 [26]. The study of further GRBs is in progress. Searches for cascade like events from GRBs have been made [27]. All-time and rolling time window searches have been performed and limits placed on models of neutrino production.

*2.4. WIMPs*

The mystery of the dark matter, responsible for some 23% of the energy density of the universe, is a target of the search for WIMPs (Weakly Interacting Massive Particles) with AMANDA. A likely dark matter candidate is the neutralino - the lightest supersymmetric particle in in most supersymmetric extensions of the standard model. After some time, these would become gravitationally trapped in the centre of the earth and sun, where they could pair-wise annihilate via several paths to produce neutrinos. Thus, AMANDA searches for excesses of neutrinos from the centre of the earth (1997-99 data [28, 29]), and from the sun (2001 data [30]). To date, neither the earth nor sun has been revealed as an annihilation site for neutralinos, and these non-observations place bounds on various parameters in the supersymmetric extensions of the standard model. Once all current data is analysed, these bounds will be competitive and complementary with those from direct detection experiments like CDMS.

*2.5. Diffuse searches*

To search for a diffuse flux of neutrinos from the sum of sources in the universe, one must look for neutrinos in excess of the expectation for atmospheric neutrinos. The extra-terrestrial flux is expected to have a harder spectrum ($\sim E^{-2}$) than the atmospheric neutrinos ($\sim E^{-3.7}$), so searches are designed where event energies are estimated. Three types of diffuse search are conducted with AMANDA, one sensitive to muon-neutrinos, and the other two sensitive to all flavours. The muon search seeks to isolate muon tracks and use event observables related to the energy. One style of all-flavour search focuses on cascade-like events - and is thus sensitive to neutral and charged current interactions of all flavours. Cascades from charged current interactions come from electron and tau neutrinos, and from some muon-neutrinos where most of the energy goes into the cascade, leaving only a short track from a low energy muon. These searches are mostly sensitive to cascade events contained in the detector volume. The second type of all-flavour search looks for large cascade and muon events from extremely high energy neutrino interactions, including events where the cascade or muon is well outside the volume of the detector. Due to attenuation of neutrinos in the earth, these searches are most sensitive to horizontal events, with the main background being energetic cosmic ray muon bundles.

Unlike a point source search, a diffuse search strictly has no "off-source" region where data can be used to estimate the background. Thus the analysis relies on theoretical predictions of the atmospheric neutrino fluxes for background estimations. In practice, the observed lower energy events are used to place some constraint on the atmospheric models before they are used to estimate the high energy background. As for other analyses, downgoing muons are used as a calibration beam to check that the detector would be sensitive to the types of high-energy events expected from extra-terrestrial neutrinos.

Table 1 summarises the results of the different searches for a diffuse flux of neutrinos with the AMANDA data sets, taken from 1997 to 2003. In the results reported here, the all-flavour analyses assume a 1:1:1 electron, muon and tau flavour mixture at the earth, due to maximal neutrino oscillations. These limits can be converted (and compared) to muon limits by dividing by three.

Two *all-flavour cascade* searches have been performed, on the 1997 [31] and 2000 [32] data sets. The limit for the 2000 data improved by an order of magnitude over that for 1997. In a similar energy range ($20 - 5 \times 10^4$ TeV), the Baikal collaboration has recently analysed 1038 days (1998-2003) of data from the NT-200 experiment, leading to a slightly better limit of $\mathrm{E}_\nu^2 \times \mathrm{dN}_\nu/\mathrm{dE}_\nu = 8.1 \times 10^{-7}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$[33].

At higher energies, these data sets have been analysed with the *all-flavour UHE* method [34, 35, 36]. Although the sensitivity of the 2000 search ( $\mathrm{E}_\nu^2 \times \mathrm{dN}_\nu/\mathrm{dE}_\nu = 3.7 \times 10^{-7}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$) was improved over 1997, the experimentally obtained limit for 2000 turned out to be the same as that for 1997, due to the observation of a non-significant excess of events. These limits are the best of any detector at energies up to $\sim$ 1PeV.

Searches for a diffuse flux, using reconstructed contained muon events, have been made on the 1997 [37], 2000 and 2000-03 data sets. For the year 2000 data set, a regularised unfolding of the energy spectrum was conducted. This spectrum was statistically compared with the atmospheric neutrino expectation and a limit on a diffuse $E^{-2}$ flux derived [16]. For the 2000-03 data, the muon analysis used the number of optical module channels per event that reported at least one Cherenkov photon ($N_{\mathrm{ch}}$) as an energy estimator. The harder expected extra-terrestrial flux would produce a flatter $N_{\mathrm{ch}}$ distribution than that for atmospheric neutrinos (see figure 1). Before looking at the data, an optimal cut of $N_{\mathrm{ch}}$ was found in order to produce the best limit setting sensitivity of the search [20, 38]. The data above this cut ($N_{\mathrm{ch}} > 100$) were kept blind while the lower $N_{\mathrm{ch}}$ events were compared to atmospheric neutrino expectations. The Bartol [14] and Honda [15] atmospheric neutrino fluxes were varied to account for systematic uncertainties, then constrained by normalisation with the low $N_{\mathrm{ch}}$ data. The remaining spread in the high $N_{\mathrm{ch}}$ region was used to calculate an error on the expected number of events above the $N_{\mathrm{ch}} > 100$ cut. The results are shown in figure 1 and compared to the data. Above the cut, 6 events were seen, where 6.1 were expected. Using the range of atmospheric uncertainty (shaded band in figure 1) in the limit calculation [39] leads to a limit on an $E^{-2}$ flux of muon-neutrinos, at the earth, of $\mathrm{E}_\nu^2 \times \mathrm{dN}_\nu/\mathrm{dE}_\nu = 8.8 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. This limit is valid in the energy range 16-2500 TeV and is the best limit of any neutrino detector to date. Limits were also placed on specific extra-terrestrial models and on the flux of prompt, charm-meson neutrinos from the earth's atmosphere [40].

### *2.6. Supernovae, cosmic ray composition, monopoles and new physics*

AMANDA is a supernova detector, with sensitive coverage of our galaxy [41]. A burst of low energy electron-neutrinos from a supernova would produce an increase in the rates of all optical modules over a short time ($\sim$ 10 seconds). The AMANDA supernova system is part of the Supernova Early Warning System (SNEWS). AMANDA, in conjunction with the SPASE surface air shower detector, has been used to study the composition of cosmic rays near the knee [42]. Searches for magnetic monopoles have been made, and Lorentz invariance and decoherence are two of the "new physics" tests being conducted with atmospheric neutrino data from AMANDA.

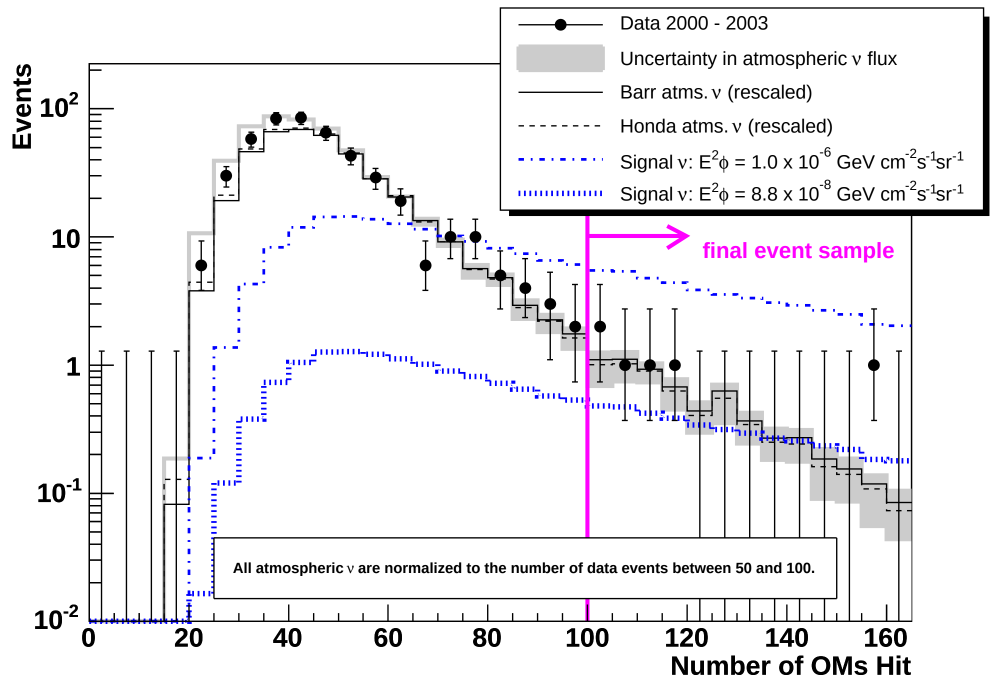


**Figure 1.** $N_{\rm ch}$ , the number of OMs triggered, for the AMANDA 2000-03 muon track diffuse analysis. The data is compared to atmospheric neutrino expectations [14, 15]. The signal prediction for an $E^{-2}$ flux is rescaled to reflect the event limit derived from the background and events above $N_{\rm ch} = 100$.

**Table 1. Summary of AMANDA diffuse neutrino flux results, 1997-2003**. The results labelled "muon" are for analyses sensitive to neutrino-induced muon tracks in the detector, and give limits on the muon-neutrino flux at earth. The "all-flavour" analyses are sensitive to events from muon, electron and tau neutrinos, and place limits on the total neutrino flux at the earth, assuming a 1:1:1 flavour ratio due to maximal mixing neutrino oscillations during propagation to the earth. Assuming this 1:1:1 flavour ratio, the muon-neutrino limits may be converted to all-flavour limits by multiplying by three.

| **Data set** | **Detection channel** | **Neutrino energy range TeV** | Limit $\mathrm{E}_\nu^2 \times \mathrm{dN}_\nu/\mathrm{dE}_\nu$(90%c.l.) GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ |
|---|---|---|---|
| 1997 | muon [37] | $6 - 10^3$ | $8.4 \times 10^{-7}$ |
| 1997 | all flavour, UHE [34] | $10^3 - 3 \times 10^6$ | $9.9 \times 10^{-7}$ |
| 1997 | all flavour, cascade [31] | $5 - 300$ | $98.0 \times 10^{-7}$ |
| 2000 | all flavour, cascade [32] | $50 - 5 \times 10^3$ | $8.6 \times 10^{-7}$ |
| 2000 | all flavour, UHE [35, 36] | $1.8 \times 10^2 - 1.8 \times 10^6$ | $9.9 \times 10^{-7}$ |
| 2000 | muon, unfolding [16] | $100 - 300$ | $2.6 \times 10^{-7}$ |
| 2000-03 | muon | $16 - 2.5 \times 10^3$ | $0.88 \times 10^{-7}$ |

## 3. IceCube: The future is now

### *3.1. Construction and Performance*

The first of the next generation kilometre scale neutrino telescopes, IceCube, will consist of an in-ice cubic kilometre neutrino detector, and a kilometre square surface cosmic ray air shower detector (IceTop). Construction began at the South Pole during the austral summer 2004-05, with 1 in-ice string, and 4 IceTop stations deployed [43]. During the second summer season, 8 more strings and 12 IceTop stations were installed. The goal is to complete construction in early 2011, with 80 strings (4800 modules) and stations (320 modules) completed. The in-ice strings will instrument a kilometre volume between 1500 and 2500 metres depth, and the IceTop array will cover a square kilometre at the surface. The same design of DOM (Digital Optical Module) is used throughout the detector. These consist of pressure spheres containing 10 inch photomultiplier tubes, the signals of which are digitised inside the module and then sent to the surface data acquisition system. The DOMs differ from the AMANDA modules in that the full time series of photons (the “waveform”) is captured.

The holes are drilled with a hot water system, taking about 30 hours to drill to the final depth, then 10 hours to ream back up, depositing more energy to leave a hole at the correct size during the string deployment. Deployment of a string takes about 12 hours - 8 hours for module attachment, 4 hours to lower to the final depth. IceTop tanks are installed in shallow trenches dug near each string location, and are filled with water, which is allowed to slowly freeze back about the modules, to prevent formation of bubbles.

The deployed hardware has performed up to expectations to date. Detailed studies of the first string and IceTop tank behaviour has been published [43]. Two upward moving events were detected with the single string, consistent with an atmospheric neutrino origin. The presently operating 9 string and 16 station detector is performing well. Upward moving neutrino events have been seen. Atmospheric muons have been tracked in the in-ice array. Air showers have been reconstructed with IceTop, and coincident events, where IceTop sees an air shower and the in-ice array sees the penetrating muons, have been studied. First physics analyses are well underway.

### *3.2. Physics potential*

An initial potential performance study for the in-ice array of IceCube was completed before construction began [44]. The simulation and reconstruction programs were those used in AMANDA, adapted to the larger IceCube detector. As such, no usage of the DOM waveform information was made in the reconstruction. The assumed flux of charm atmospheric neutrinos [45] was chosen conservatively; if in reality this background turns out smaller, then the predicted sensitivities will be better than those quoted. A median angular resolution of better than $1^\circ$ is seen for muon energies greater than 1 TeV. The effective area for muon detection exceeds the geometric kilometre area at 10 TeV, rising to 1.4 square kilometres for events in the 1 to 100 PeV energy range. The sensitivity to diffuse and point sources of neutrinos has been estimated. For three to five years of observation, the limit on an $E^{-2}$ flux of diffuse neutrinos would be about thirty times smaller than the AMANDA-II four-year muon limit (section 2.5), and a flux one-tenth of the AMANDA-II limit would be detectable at $5\sigma$ significance in that time. For point sources, similar results are obtained. For GRBs, the Waxman-Bahcall flux would be constrained after the observation of about 100 GRBs, and 500 GRBs would be needed to observe that flux at a $5\sigma$ significance.

## 4. Conclusions

The long-held dream of a large volume, high energy neutrino detector is finally a reality at the South Pole. The last decade has been one of technology, deployment, and analysis development with the AMANDA detector, leading to the design and construction of IceCube. IceCube, slated for completion in 2011, is already producing physics data, and once completed, will have unprecedented sensitivity to sources of extra-terrestrial neutrinos, hopefully leading to new discoveries about the nature of the cosmos.

## References


[1] For more information, see the IceCube website: http://icecube.wisc.edu

[2] Gaisser T K, Halzen F and Stanev T 1995 *Phys. Rept.* **258** 173 [*Erratum* 1995 **271** 355 ], hep-ph/9410384; Learned J G and Mannheim K 2000 *Ann. Rev. Nucl. Part. Science* **50** 679; Halzen F and Hooper D 2002 *Rept. Prog. Phys.* **65** 1025, arXiv:astro-ph/0204527; Halzen F 2006 *Proc. of 'The multi-messenger approach to high-energy gamma ray sources,'* Barcelona

[3] Lowder D M, Miller T, Price P B, Westphal A, Barwick S W, Halzen F and Morse R 1991 *Nature* **353** 331

[4] Askebjer P *et al* 1995 *Science* **267** 1147-1150

[5] Ackermann M *et al* 2006 *Journal of Geophysical Research* **111** D13203

[6] Ackermann M *et al* 2006 *Nucl. Inst. and Meth. in Phys. Res.*, A. **556** 169

[7] Andres E *et al* 2000 *Astropart. Phys.* **13** 1

[8] Karle A, for the AMANDA collaboration 1999 *Proc. 26th ICRC, Salt Lake City, Utah*

[9] Ahrens J *et al* 2004 *Nuclear Instruments and Methods in Physics Research* A **524** 169

[10] Ahrens J *et al* 2002 *Phys. Rev.* D **66**, 012005

[11] Andres E *et al* 2001 *Nature* **410** 441

[12] Ackermann M, for the IceCube Collaboration 2006 *Proc. of 'The multi-messenger approach to high-energy gamma ray sources,'* Barcelona

[13] Achterberg A *et al* 2006 to be submitted to *Phys. Rev. D.*

[14] Barr G D, Gaisser T K, Lipari P, Robbins S and Stanev T 2004 *Phys. Rev.* D **70**, 023006

[15] Honda M, Kajita T, Kasahara K and Midorikawa S 2004 *Phys. Rev.* D **70**, 043008

[16] K. Münich for the IceCube Collaboration 2005 2005 Proc. 29th Int. Cosmic Ray Conf., Pune

[17] Ahrens J *et al* 2003 *Astrophys. J* **583** 1040

[18] Ahrens J *et al* 2004 *Phys. Rev. Lett.* **92** 071102

[19] Ackermann M *et al* 2005 *Phys. Rev.* D **71** 077102

[20] Hill G C and Rawlins K 2003 *Astropart. Phys.* **19** 393

[21] Achterberg A *et al* 2006 *Astroparticle Physics*, accepted

[22] Achterberg A *et al* 2006 *Phys. Rev. Lett.* accepted for publication

[23] Kelley J L for the IceCube Collaboration 2005 Proc. 29th Int. Cosmic Ray Conf., Pune

[24] Waxman E and Bahcall J 1997 *Phys. Rev. Lett.* **78** 2292-2295

[25] Kuehn K for the IceCube Collaboration and the IPN Collaboration 2005 Proc. 29th Int. Cosmic Ray Conf., Pune

[26] Stamatikos M, Kurtzweil J and Clarke M J for the IceCube Collaboration (*Preprint:* astro-ph/0510336)

[27] Hughey B and Taboada I for the IceCube Collaboration, 2005 Proc. 29th Int. Cosmic Ray Conf., Pune

[28] Ahrens J *et al* 2002 *Phys. Rev.* D **66** 032006

[29] Achterberg A *et al* 2006 *Astropart. Phys.* in press

[30] Achterberg A *et al* 2006 *Astropart. Phys.* **24** 456-466

[31] Ahrens J *et al* 2003 *Phys. Rev.* D **67** 012003

[32] Ackermann M *et al* 2004 *Astropart. Phys.* **22** 127

[33] Dzhilkibaev Z *et al* 2006 *Astropart. Phys.* **25** 140

[34] Ackermann M *et al* 2005 *Astropart. Phys.* **22** 339

[35] Gerhardt L for the IceCube Collaboration, 2005 Proc. 29th Int. Cosmic Ray Conf., Pune

[36] Gerhardt L for the IceCube Collaboration 2006 Proc. SUSY06

[37] Ahrens J *et al* 2003 *Phys. Rev. Lett.* **90** 251101

[38] Hodges J for the IceCube Collaboration, 2005 Proc. 29th Int. Cosmic Ray Conf., Pune

[39] Cousins R D and Highland V L 1992 *Nucl. Ins. Meth. Phys. Res.* **A320** 331, Feldman G and Cousins R 1998 *Phys. Rev.* D **57** 3873, Conrad J, Botner O, Hallgren A and de los Heros C 2003 *Phys. Rev.* D **67** 012002, Hill G C 2003 *Phys. Rev.* D 118101

[40] Hodges J for the IceCube Collaboration 2006 *Proc. TeV Particle Astrophysics II,* Madison, to appear in *J. Phys.: Conf. Series*

[41] Ahrens J *et al* 2002 *Astropart. Phys.* **16** 345

[42] Ahrens J *et al* (AMANDA and SPASE Collaborations) 2004 *Astropart. Phys.* **21** 565

[43] Achterberg A *et al* 2006 *Astropart. Phys.* doi:10.1016/j.astropartphys.2006.06.007

[44] Ahrens J *et al* 2004 *Astropart. Phys.* **20** 507

[45] Bugaev E V *et al* 1998 *Phys. Rev. D* **58** 054001